CLOUD BASE HEIGHT
VISIBLE/INFRARED IMAGER/RADIOMETER SUITE ALGORITHM THEORETICAL BASIS DOCUMENT

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GLOSSARY OF ACRONYMS

AMSR	Advanced Microwave Scanning Radiometer
ATBD	Algorithm Theoretical Basis Document
CIWP	Cloud Ice Water Path
CLW	Cloud Liquid Water
CMIS	Conical Scanning Microwave Imager/Sounder
DMSP	Defense Meteorological Satellite Program
EDR	Environmental Data Record
EOS	Earth Observing System
HCS	Horizontal Cell Size
HRI	Horizontal Reporting Interval
HSR	Horizontal Spatial Resolution
IPO	Integrated Program Office
IWC	Ice Water Content
IWP	Ice Water Path
LWC	Liquid Water Content
LWP	Liquid Water Path
MODIS	Moderate Resolution Imaging Spectroradiometer
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
PACEOS™	Performance and Analyses Capabilities for Earth Observing Systems
SRD	Sensor Requirements Document
SSM/T-2	Special Sensor Microwave Moisture Profiler
TBD	To be determined
TBR	To be resolved
VIIRS	Visible/Infrared Imager/Radiometer Suite

ABSTRACT

This Algorithm Theoretical Basis Document (ATBD) describes the methodology developed to retrieve the Cloud Base Height Environmental Data Record (EDR) from VIIRS imagery. The Cloud Base Height EDR is derived by subtracting cloud thickness from cloud top height. Cloud thickness is retrieved from parameterized equations for ice and water clouds using cloud optical depth and cloud effective particle-size EDRs. Thus, the retrieval of the Cloud Base Height EDR requires the analysis of cloud top phase as a derived requirement. The accuracy of these ancillary cloud EDRs is covered in separate VIIRS algorithm theoretical basis documents.

This document presents the theoretical basis and the pre-launch agenda for the Cloud Base Height EDR. It includes an in-depth analysis of the retrieval approach for use with water clouds and ice clouds, results of sensitivity analyses, and performance summary for the EDR from extensive simulations. It also identifies primary and ancillary data requirements, and provides a risk reduction plan for developing, testing, and validating the performance of the algorithm to meet VIIRS threshold requirements in the post-launch timeframe.

We are greatly encouraged by the results presented in this algorithm theoretical basis document. While the Cloud Base Height EDR is considered extremely important to civilian and military aircraft operations as well as weather and climate prediction, it is the only cloud EDR listed as a Category III requirement. Perhaps the failure to make it a Category II EDR reflects the lack of confidence that useful cloud base height information can be retrieved solely from satellite-based sensors more than the need for such information by the user community. However, results presented in this document are in good agreement with those recently reported in the refereed literature (Wilheit and Hutchison, 2000) that demonstrated the measurement uncertainty in cloud base heights that can be acheived with microwave moisture sounder data constrained by IR cloud top temperatures. The predicted performance in the retrieval of cloud base heights from two completely different (CMIS and VIIRS) sensors that exploit totally different phenomenology strongly suggests that useful cloud base heights, of about 1 km measurement uncertainty, are achievable during the NPOESS era.   Therefore, it is our hope that these results will encourage the user community to upgrade the cloud base height data product from Category III to Category II EDR.

1.0   INTRODUCTION

1.1   PURPOSE

This algorithm theoretical basis document (ATBD) describes the phenomenology associated with the retrieval of cloud base heights from a Visible/Infrared Imager/Radiometer Suite (VIIRS) sensor in order to satisfy the requirements established by the Integrated Program Office (IPO) of the National Polar-orbiting Operational Environmental Satellite System (NPOESS).

1.2   SCOPE

In addition to this Introduction, the ATBD holds four sections. Section 2 describes the NPOESS program requirements and retrieval strategy along with a new specification of expected performance of the Cloud Base Height EDR. A complete definition of the theoretical basis for the retrieval of cloud base height is found in Section 3, including input parameters, processing sequence, mathematical description of the algorithms for ice and water clouds, performance summary based upon an error budget, results of sensitivity studies, and practical considerations for hosting the algorithm, along with an evaluation plan and a schedule to complete the validation algorithm performance against requirements. Section 4 identifies assumptions and the resultant limitations of the cloud base height retrieval algorithm. Conclusions are summarized in Section 5.

1.3   VIIRS DOCUMENTS

This ATBD addresses program requirements specified by the NPOESS IPO in Version 2, Revision because of the VIIRS Sensor Requirements Document (SRD), dated March 7, 2000.

1.4   REVISIONS

This is version 3 of this document, and is dated May 2000. Version 1 was produced in October 1998 and version 2 in June, 1999. This revision includes performance summary results and EDR error budgets based upon simulations of VIIRS cloud EDRs that are ancillary data products for the retrieval of the Cloud Base Height EDR.

2.0   EXPERIMENT OVERVIEW

2.1   PROGRAM REQUIREMENTS FOR CLOUD BASE HEIGHT RETRIEVALS

Minimum acceptable (threshold) program requirements and program goals (objectives) for the retrieval of cloud base heights from the VIIRS sensor are shown in Table 1. Also included is the "specification," which represents the expected EDR values to be delivered by all Cloud Base Height algorithms.

Table 1. Cloud base height requirements from March 7, 2000 VIIRS SRD.

Para. No.	Attribute	Thresholds	Objectives	New Specification Value
V40.4.1-1	a. Horizontal Cell Size	25 km	10 km	25 km worst case 5 km fine, at nadir
V40.4.1-2	b. Horizontal Reporting Interval	(TBD)	(TBD)	HCS
V40.4.1-3	c. Horizontal Coverage	Global	Global	Global
	d. Vertical Cell Size	N/A	N/A	N/A
V40.4.1-4	e. Vertical Reporting Interval	Base of lowest cloud layer	Base of all distinct cloud layers	Base of highest and lowest cloud layers
V40.4.1-5	f. Measurement Range	0 - 15 km	0 - 30 km	0 – 20 km
V40.4.1-6	g. Measurement Uncertainty	2 km (TBR)	0.25 km	1.4 km for ice clouds , 0.8 km for water clouds
V40.4.1-7	h. Mapping Uncertainty	4 km	1 km	4 km
	i. Maximum Local Average Revisit Time	6 hrs	4 hrs	6 hrs
	j. Maximum Local Refresh	(TBD)	(TBD)	6 hrs
V40.4.1-8	l. Minimum Swath Width	3000 km (TBR)	(TBD)	3000 km

Cloud base height is defined as the height above ground level where cloud bases occur. More precisely, for a cloud-covered Earth location, cloud base height is the set of altitudes of the bases of the clouds that intersect the local vertical at this location. The reported heights are horizontal spatial averages over a cell, i.e., a square region of the Earth's surface. If a cloud layer does not extend over an entire cell, the spatial average is limited to the portion of the cell that is covered by the layer. As a threshold, only the height of the base of the lowest cloud layer is required, and the objective is to report cloud base height for all distinct cloud layers.

2.2   INSTRUMENT CHARACTERISTICS

Cloud base height is derived from other VIIRS environmental data records (EDRs). It has no effect on the VIIRS design.

2.3   RETRIEVAL STRATEGY

The Cloud Base Height EDR is derived by subtracting cloud thickness from cloud top height. Cloud thickness is retrieved using cloud optical depth and cloud-effective particle-size EDRs, which vary greatly between ice and water clouds. Thus, the retrieval of the Cloud Base Height EDR requires the analysis of cloud top phase as a derived requirement. The accuracy of retrieved cloud top heights from VIIRS data also depends on (1) cloud top phase, (2) the number of cloud layers within the VIIRS Horizontal Spatial Resolution (HSR), and (3) the surface background/terrain. Therefore, quality flags are used to identify the confidence that retrieved cloud base heights comply with VIIRS threshold requirements for the Horizontal Cell Size (HCS) and the Horizontal Reporting Interval (HRI). The retrieval accuracy of ancillary cloud EDRs used in the Cloud Base Height algorithm are covered in separate documents.

3.0   ALGORITHM DESCRIPTION

There are four executable modules or algorithms, which may be used to retrieve the Cloud Base Height EDR. Two are used for the retrieval of Cloud Base Height when a single-layer of water cloud or ice cloud is determined to be present within the HSR of the VIIRS sensor. These algorithms and sensitivities studies using them are described in Sections 3.1-3.4. The third algorithm is used when multi-layered cloud are found within a single VIIRS HSR and it is described in Section 3.5.   The fourth module, which remains a research area, incorporates any Cloud Base Height reported by conventional weather observations with those retrieved from the VIIRS and assigns a confidence flag to the merged Cloud Base Height EDR. (The "Merge Module" is still under development and is not covered in this version of the ATBD.)

The retrieval approach utilizes ancillary cloud EDRs from both the NPOESS VIIRS and microwave sensors depending upon the retrieved optical thickness of the cloud using the VIIRS data. If the cloud optical thickness exceeds the measurement range for the VIIRS EDR, ancillary data from the microwave imagery is assumed to satisfy NPOESS threshold requirements and used in the analysis of Cloud Base Height. In reality, some ancillary data used in the Cloud Base Height algorithms are considered high risk of meeting NPOESS system threshold requirements, e.g., CMIS cloud liquid water over land surfaces. Therefore, confidence measures are assigned to retrieved cloud bases according the data used in the analysis and surface characteristics within the HSR. A discussion on the definitions of these quality flags is contained in Section 3.6. Ultimately, in the post-PDR era, these quality flag definitions will be amended, e.g., to incorporate conventional meteorological reports; however, additional research is needed and scheduled as part of the algorithm validation effort.

3.1   PROCESSING OUTLINE

The processing sequence for the cloud base height retrieval algorithm for water clouds is shown in Figure 1. The equivalent sequence for ice clouds is shown in Figure 2.
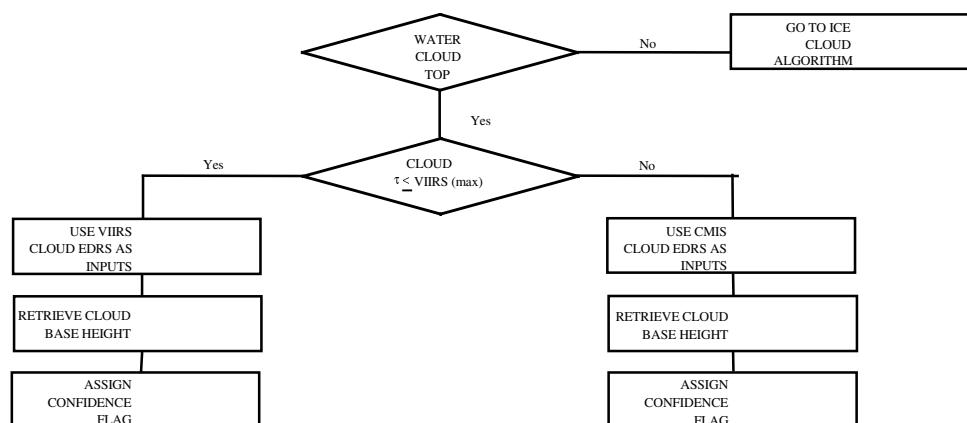
Figure 1. Processing sequence for the retrieval of single layered water clouds.
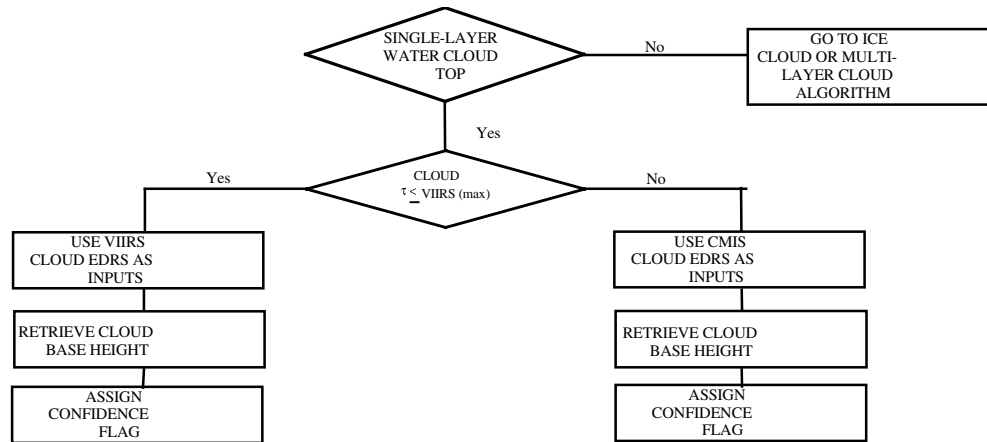
Figure 2. Processing sequence for the retrieval of single layered ice clouds.

3.2   ALGORITHM INPUT

Input parameters for Cloud Base Height retrieval algorithm are contained in Figure 3. The input parameters are real numbers. A complete description of the retrieval algorithms is contained in Section 3.3.
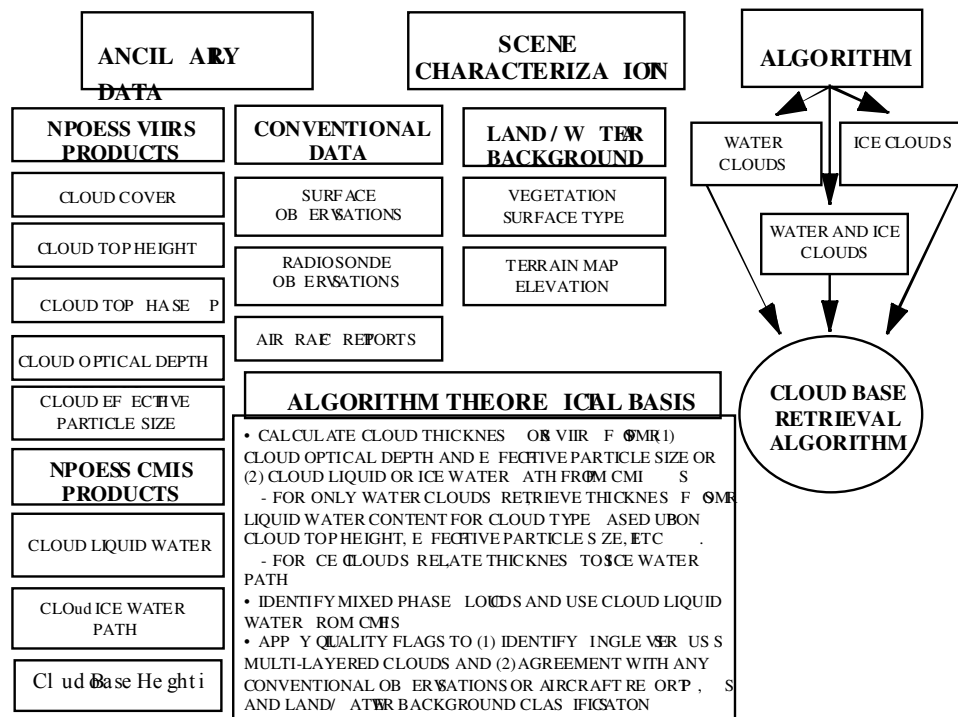
Figure 3. VIIRS EDRs and ancillary databases for the retrieval of the VIIRS Cloud Base Height EDR.

3.2.1 VIIRS Data

Input parameters from VIIRS include cloud cover, cloud top height, cloud optical depth, and cloud effective particle size. In addition, a derived VIIRS requirement is established for the retrieval of the cloud top phase in order to classify cloud optical depth and cloud effective particle size accurately, establish the presence of multi-layered clouds versus single-layered clouds.

3.2.2 Non-VIIRS Data

Input parameters from the CMIS and other (non-VIIRS) ancillary databases include cloud liquid water and cloud ice water paths from the CMIS along with land/water background and surface terrain (e.g., mountainous versus flat). Additionally, cloud base heights retrieved from the CMIS sensor will be used, especially for multi-layered cloud systems, as discussed in Section 4. (Note: Throughout the remainder of this document, references to CMIS equate to ancillary microwave moisture sounder data, microwave imagery data, and/or derived data products from these NPOESS sensors.)

3.3 THEORETICAL DESCRIPTION OF CLOUD BASE HEIGHT RETRIEVAL

3.3.1 Physics of the Problem

Cloud Base Height is retrieved only for pixels that are classified as cloudy in the cloud cover EDR. Because the threshold requirement for the cloud cover EDR has a measurement uncertainty of 10 percent, the Cloud Base Height algorithm must be capable of recognizing and reporting contradictory information in the form of an analysis confidence or quality flag.

Cloud Base Height requires the accurate analysis of numerous cloud EDRs of which cloud top height is most critical. Cloud top height is more accurately analyzed when water clouds are present, as compared to ice clouds (Hutchison *et al*., 1997); thus, quality or confidence flags must also be set to differentiate between these two cloud types and cloud top phase becomes a derived requirement for use in the Cloud Base Height EDR. If a water cloud is present, cloud top height is accurately analyzed using brightness temperatures from a band centered near 10.8 μm, after correcting for atmospheric attenuation due primarily to water vapor, and temperature profiles from the CrIS, the CMIS, or some numerical model. However, if ice cloud tops are present, it may be necessary to retrieve the cloud top pressure first, and then the cloud top height and temperature using atmospheric profile information (Hutchison *et al.,* 1997). Alternatively, the effective cloud height may be retrieved along with optical depth and effective particle size (Ou *et al*., 1993); however, this usually means a layered-mean cloud height is retrieved rather than the actual cloud top height, which can significantly impact the Cloud Base Height EDR. In accordance with the cloud top height EDR threshold requirement, it was initially assumed that cloud top heights would be more accurately known for optically thicker (TBR) clouds [1.0 km (TBR)] than for optically thinner (TBR) clouds [2.0 km]. (Retrieved measurement accuracies for cloud top height are reported as 1.4 km and 0.8 km for ice and water clouds, respectively.) Thus, it is now confirmed that all ancillary VIIRS EDRs will meet thresholds and be available for use with the Cloud Base Height algorithm, including (1) the Cloud Cover EDR,(2) the Cloud Top Height EDR, and (3) the cloud top phase as a derived requirement. It is also necessary to identify

the presence of single versus multiple cloud layers. Cloud Base Height analyses are optimal when only a single cloud layer exists within the HCS.

The next and most critical step in preparation for the analysis of cloud base heights is to retrieve cloud effective particle size and cloud optical thickness. The algorithms to satisfy these threshold requirements are mature and follow the approach to exploit reflected solar energy during the daytime (King *et al.*, 1997; Rao *et al.*, 1995) and thermal emissions during nighttime conditions (Ou *et al.*, 1995; Ou *et al.*, 1993). The total error analyses necessary to complete the system definition flowdown for these critical EDRs has been completed and integrated into the performance summary for the Cloud Base Height algorithm as shown in Section 3.3.4.1.

The final step in the retrieval of Cloud Base Height relates cloud optical thickness to cloud thickness, which is done by the cloud particle scattering phase function or scattering coefficient. However, scattering coefficient is a function of several other cloud EDRs, including (a) the number density distribution of water droplets or ice crystals, e.g., effective particle size; (b) the single scattering albedo; and (c) the indices of refraction at the VIIRS wavelengths.

Finally, an overall confidence measure or quality flag must be assigned to the retrieved Cloud Base Height EDR. The quality flag is an assessment of any contradictory information processed from VIIRS cloud EDRs or conventional meteorological reports that might be available. The quality flag is also a function of (1) the number of cloud layers determined present in the horizontal cell, (2) the cloud top phase of the highest cloud, and (3) background scene characteristics such as terrain elevation and vegetation index/surface class. A more complete discussion of retrieved accuracy and confidence flags is presented in Section 3.5.4.

3.3.2   Mathematical Description of the Algorithms

The Cloud Base Height algorithms information from VIIRS imagery and supplemental databases obtained from meteorological satellite sensors and conventional weather data are shown in Figure 3. The methodology, overviewed in Figure 4, assumes the accurate specification of several VIIRS cloud EDRs in general and cloud top height (Z_{ct}) in particular.

Cloud Base Height (Z_{cb}) is determined by subtracting cloud thickness (ΔZ) from cloud top height while ΔZ is derived from retrieved liquid water path (LWP), in the case of a water cloud or ice water path (IWP) in the case of an ice cloud, as shown in Equations 1 and 2, respectively. LWP is defined as the integration of liquid water content (LWC) across cloud thickness where LWC is obtained from *a priori* information on the cloud particle size distributions and cloud type, e.g., altostratus, stratocumulus, and others. Similarly, IWP is defined as the integration of ice water content (IWC) over the thickness of the cirrus cloud.

Results of sensitivity studies reported in Section 3.4.3.4 show that errors in retrieved Cloud Base Height are not sufficiently to levy cloud type as a derived requirement for the VIIRS sensor. Sufficient accuracy in retrieved Cloud Base Height can be achieved using mean LWC values for low-level versus mid-level water clouds.
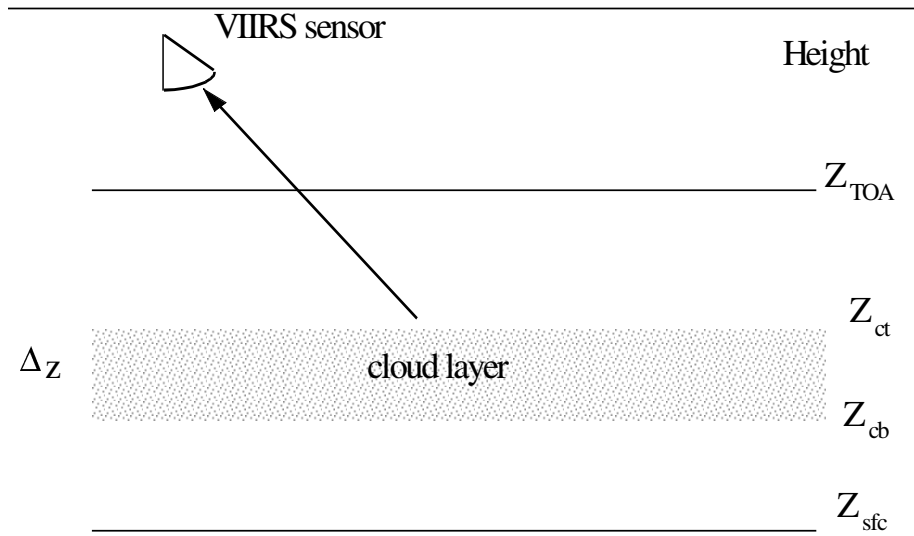
**Figure 4. Overview of the methodology used to retrieve the
Cloud Base Height EDR from VIIRS data.**

3.3.2.1 Water Clouds

For water clouds, LWP has been related to cloud optical depth or thickness (τ) and cloud effective cloud particle size (r_{eff}) as shown in Equation 2 (Liou, 1992). Because the upper limit of the VIIRS threshold measurement range for cloud optical thickness is 10 (TBR), the cloud liquid water (CLW) EDR product retrieved from the CMIS sensor is used directly for LWP if this upper limit is exceeded as shown in Equation 3.

$$Z_{cb} = Z_{ct} - (\Delta Z) = Z_{ct} - [LWP/LWC] \tag{1}$$

(1) $\tau <= 64$

$$LWP = [2\,\tau\,r_{eff}] / 3 \tag{2}$$

where LWP is in gm/m^2

(2) $\tau > 64$

$$LWP = CLW\ EDR\ from\ CMIS \tag{3}$$

and CLW in mm = 10^{-3} g/m^2.

3.3.2.2 Ice Clouds

When ice clouds are present, the form of the equation for the retrieval of the Cloud Base Height EDR is similar to that for water clouds with the exception that the relevant terms are now IWP and IWC rather than LWP and LWC. The parameterization for IWP is a function of the ice

crystal size distribution and ice crystal diameter ($D_e=2r_{eff}$) (Liou, 1992). Additionally, D_e and thus IWP are functions of cloud temperature.

$$Z_{cb} = Z_{ct} - (\Delta Z) = Z_{ct} - [IWP/IWC] \qquad (4)$$

$$(1) \qquad \tau < = 10$$

$$IWP = \tau / [a+b/D_e] \qquad (5)$$

with a and b being regression coefficients, defined by Liou (1992).

$$(2) \qquad \tau > 10$$

$$IWP = CIWP \ EDR \ from \ CMIS \qquad (6)$$

where CIWP is reported in g/m^2.

3.3.3 Archived Algorithm Output

There are two outputs from the Single-Layered Water and Ice Cloud Base Height Algorithms: (1) a retrieved cloud base height in meters above ground level and (2) a Confidence Flag. Eventually, the confidence flag will include the use of conventional data; however, additional research is needed to determine how best to include these data in the measure of confidence. Definitions of the confidence flags are provided in Section 3.6.4, entitled Quality Assessment and Diagnostics.

3.3.4 Variance and Uncertainty Estimates

Analyses show the 1-σ measurement uncertainty for the retrieval of the VIIRS Cloud Base Height EDR in a single cloud-layered ice cloud system to be 1.4 km and 0.8 km for a similar water cloud system.

3.3.4.1 Error Budget

An error budget for the Cloud Base Height EDR has been completed using the measurement accuracies of ancillary VIIRS cloud EDRs , including cloud top height, optical depth, and effective particle size. These data are shown in Figure 5 according to cloud top phase.

Figure 5 contains the threshold and objective requirements for key attributes of the Cloud Base Height EDR. Also included are Spec-values, from the A-specification completed in 1998, and Predicted Performance, which is based upon most recently completed simulations. Values of Predicted Performance supercede A-Specifications.   Examination of the table shows the following:

1.   Initial estimates on the accuracy of the retrieved Cloud Base Height EDR were conservative. Performance should meet threshold requirements for both ice clouds (1.4 km) and water clouds (0.8 km).

2. While initial estimates assumed the capability to retrieve cloud bases in a single cloud-layered system, adequate margins in (1) lead to optimism that meaningful cloud bases heights can be retrieved in two cloud-layered conditions. Therefore, we believe the Cloud Base Height EDR will be better than threshold rather than worse than threshold as reported earlier in the A-specification. While this capability will be case dependent, i.e., results will be optimum if all layers are water clouds and CLW is available and meets threshold requirements for the microwave sensor. Poorer results are obtained when cirrus clouds are present over another cloud layer.

Cloud Base Height	Threshold	Objective	Spec	**Pred Perf**	Comment
a. Horizontal Cell Size (km)					
1. Mod, worst case	25	10	25	25	
2. Fine, at nadir	5	TBD	5	5	per Cloud Top Height EDR
b. Horizontal Reporting Interval	TBD	TBD	HCS	HCS	
c. Horizontal Coverage	Global	Global	Global	Global	
d. Vertical Cell Size	N/A	N/A	N/A	N/A	
e. Vertical Reporting Interval	Base of lowest cloud layer	Base of all distinct cloud layers	Base of highest cloud layer	Base of highest and lowest cloud layers	Assumes microwave data available
f. Measurement Range	0-15 km	0 - 30 km	0 - 20 km	0 - 20 km	per Cloud Top Height EDR
g. Measurement Uncertainty (fine HCS Product)					
1. Water Clouds	2 km (TBR)	0.25 km	2.0 km	0.8	
2. Ice Clouds	2 km (TBR)	0.25 km	2.0 km	1.4	
h. Mapping Uncertainty	4 km	1 km	See final spreadsheet	See final spreadsheet	per Cloud Top Height EDR
k. Minimum Swath Width (All other EDR thresholds met)	3000 km (TBR)	TBD	3000 km	3000 km	per all other cloud EDRs

Better Than Threshold   **Meets Threshold**   **Worse Than Threshold**   **Not Applicable**

Figure 5. Performance summary for the Cloud Base Height EDR.

3.4 ALGORITHM SENSITIVITY STUDIES

3.4.1 Calibration Errors

Not applicable to the Cloud Base Height EDR. They are included in the error budgets for other cloud EDRs.

3.4.2 Instrument Noise

Not applicable to the Cloud Base Height EDR. They are included in the error budgets for other cloud EDRs..

3.4.3 Ancillary Data

Sensitivity analyses have been completed to quantify the expected errors in using the cloud base height algorithms as a function of ancillary data. Key cloud EDRs that are used in the retrieval of

cloud base height for water and ice clouds are cloud top height, cloud optical depth, and cloud effective particle size. In turn, these cloud EDRs are a function of cloud top temperature and cloud top phase along with cloud particle size distribution, which is also a function of cloud effective particle size and cloud top temperature.

3.4.3.1   Thickness of Common Ice and Water Clouds of Maximum VIIRS Optical Depths

The upper limit of cloud thickness, which can be retrieved solely from VIIRS data using the Cloud Base Height algorithm, is derived from the requirement for measurement range of optical depth coupled with the effective particle radius associated with different cloud types, e.g., LWC. Optical depth is measured in two wavelength ranges, 450 (TBR) nm and 845 (TBR) nm. The VIIRS SRD states that the required measurement range is 0-10, but studies demonstrated that Raytheon could increase the maximum value to 64 for water clouds and still meet threshold requirements. Thus, the maximum water cloud thickness that can be retrieved, as a function of cloud type, is defined as:

$$\Delta z_{max} = LWP/LWC = 2\,\tau\,r_e\,/\,(3\,LWC)$$

$$= 2\,(10)\,r_e\,/\,(3\,LWC) \tag{7}$$

while, for ice clouds:

$$\Delta z_{max} = IWP/IWC = \tau\,/\,[(a+b/D_e)\,IWC] \tag{8}$$

Table 2 shows the maximum cloud thickness which can be retrieved under the constraint that $\tau <= 10$, for ice clouds and $\tau <= 64$ for water clouds, based upon cloud distributions taken from Liou (Table 4.2, 1992).

Table 2. Thickness of common ice clouds with an optical thickness of 10 and water cloud clouds with an optical thickness of 64.

Cloud Type	r_e (µm)	LWC (g/m²)	Δz_{max}(m)
Stratus I (oceans)	3.5	0.24	622
Stratus II (land)	4.5	0.44	436
Stratocumulus	4.0	0.09	1896
Altostratus	4.5	0.41	468
Cirrus	~ 100 (= D_e)	~ 0.01 (= IWC)	3333

3.4.3.2   Use of Cloud Liquid Water Content from the CMIS Sensor

From Table 2, it appears that a Cloud Base Height retrieval algorithm based solely upon data from the VIIRS may have more limited utility in the presence of water clouds because the optical thickness threshold requirement measurement range of 64 is more quickly exceeded by relatively

thin cloud layers, when compared to the range for cirrus clouds. Thus it becomes necessary to use LWP information from the CMIS sensor, i.e., cloud liquid water (CLW) EDR, as an alternative data source. The threshold measurement range for the CLW EDR is 0-50 mm, and the upper limit translates to an LWP of 50,000 g/m^2 which increases Δz_{max} to over 100,000 meters for typical water clouds. Thus, using the CLW EDR from the CMIS sensor provides an alternative source of ice water path and liquid water path data and extends the range of cloud thickness that might be retrieved using the Cloud Base Height algorithms.

The assumption is made that the CMIS sensor will provide a CLW EDR that satisfies threshold requirements, i.e., meets measurement range and accuracy requirements over both land and ocean backgrounds, e.g., 0.5 mm and 0.25 mm, respectively. Analyses show that a 0.5 mm error in CLW results in about 1,250 meter error in cloud base for a typical stratus cloud over water. There is concern that the CMIS CLW EDR accuracy requirements over land may not be satisfied, i.e., it is assumed that LWP over land surfaces is more accurately retrieved from a VIIRS than a CMIS sensor. Therefore, cloud thickness values associated with optical depths that exceed 64 must contain a quality flag that identifies the use of CMIS versus VIIRS data in the Cloud Base Height analysis.

3.4.3.3 Use of Cloud Ice Liquid Water Content from the CMIS Sensor

From Table 2, it appears that a Cloud Base Height retrieval algorithm using only VIIRS data is less limited in the presence of cirrus clouds; however, information from the CMIS cloud ice water path (CIWP) EDR continues to serve an alternative data source. The threshold measurement range for the CIWP EDR is 0-2.6 kg/m^2 (or 2600 g/m^2) with an accuracy requirement of 10 percent or 5 g/m^2, whichever is greater. The upper limit of the CIWP EDR increases Δz_{max} to over 260,000 meters for cirrus clouds with an IWC of 0.01. Using the CIWP EDR from the CMIS provides a supplemental source of ice water path information for the Cloud Base Height retrieval algorithm. Thus, the measurement range for the CIWP EDR exceeds that needed to handle cirrus clouds in the troposphere. Finally, an error of 5 g/m^2 in CIWP alone translates into a Cloud Base Height error of 500 meters, while a 10 percent error causes a maximum Cloud Base Height error of 2,600 meters. Again, there is reason for concern that the CMIS CIWP EDR accuracy requirements over land may not be satisfied and quality flags are used to identify the use of CMIS data.

3.4.3.4 Sensitivity to Errors in Input Parameters

A sensitivity analysis shows that the most critical cloud EDR that directly effects cloud base height accuracy is cloud top height. Errors in optical thickness, effective particle size, and size distribution models are secondary over the range of thresholds required by the cloud optical thickness EDR, i.e., 0-10. At the larger ranges, e.g., $\tau = 64$, errors in the calculation of cloud thickness become more important; but, other factors loom as potentially larger problems, such as the ability to meet the CIWP EDR threshold accuracy requirement of 0.5 mm over land with the CMIS sensor.

Errors in retrieved cloud optical thickness

Table 3 shows the impact of errors in cloud optical depth on retrieved Cloud Base Height for a stratus cloud over the ocean, which typically has an effective particle size of 3.5 microns, and liquid water content of 0.24 g/m^3 (Liou, 1992). The cloud top height was assumed to be 2 km and the optical depth, 10. Table 4 shows similar results for cloud optical thickness of 64.

Table 3. Impact of errors in optical depth on retrieved Cloud Base Height for stratus (water) clouds with cloud top height of 2 km, optical thickness 10, effective particle size 3.5 microns, and liquid water content of 0.24 g/m^3.

Error in τ (%)	Retrieved Cloud Base Height (m)	Error in Base Height (%)	Calculated Cloud Thickness (m)	Error in Cloud Thickness (%)
0	1902.8	0	97.2	0
10	1912.5	0.5	87.5	10
20	1922.2	1.0	77.8	20
50	1951.4	2.5	48.6	50

The results in Table 3 show that the relationship between error in optical thickness and retrieved cloud thickness is 1:1, as expected for a linear system. However, the impact of this error on Cloud Base Height is less significant because the cloud thickness is relatively small for optical thickness values of 10 or less. Thus, the magnitude of the error in Cloud Base Height remains relatively unaffected by any error in cloud retrieved optical thickness. In fact, a 20 percent error in optical depth for an input optical thickness 100, which represents a stratus cloud of about 1 km thickness, only causes errors in cloud base heights of about 200 meters. Because stratus clouds are normally much thinner, the 1 km thick cloud might be considered a worst-case scenario (Liou, 1992).

Table 4. Impact of errors in optical depth on retrieved Cloud Base Height for stratus (water) clouds with cloud top height of 2 km, optical thickness 64, effective particle size 3.5 microns, and liquid water content of 0.24 g/m^3.

Error in τ (%)	Retrieved Cloud Base Height (m)	Error in Base Height (%)	Calculated Cloud Thickness (m)	Error in Cloud Thickness (%)
0	1378	0	622	0
10	1440	4.5	560	10
20	1502	9.0	498	19.9
50	1688	22.5	312	49.8

Results in Table 4 show that the relative errors (percent) in retrieved Cloud Base Height and Cloud Thickness increase significantly as the Cloud Optical Thickness is increased from 10 to 64. However, these error in retrieved Cloud Base Height remains well within the threshold requirement of 2 km even when errors in the Optical Thickness reach 50 percent, actual cloud thickness is 622 m while retrieved cloud thickness is 312 m - a difference of only 310 m.

One the other hand, optical depth values of 10 represent a much thicker ice cloud, as compared to water clouds, as shown in Tables 1-3. In the case of the cirrus cloud shown in Table 5, the magnitude of the error in retrieved Cloud Base Height becomes larger because the cloud is relatively thick, i.e., 3310.8 m. However, 50 percent errors in the optical thickness input parameter still allows the retrieved Cloud Base Height to meet the 2 km measurement uncertainty, which is the threshold requirement. Thus, the accuracy of Cloud Base Height EDR is affected most by the accuracy of the retrieved cloud top heights.

Currently, the cloud top height EDR specifies a measurement uncertainty of 1 km for optical thickness values that exceed 0.1 and 2 km for values less than 0.1; however, the Cloud Base Height threshold requirement makes no such distinction. This apparent oversight should be changed and an ICSR has been submitted for resolution. It should be noted that for optically thin clouds, the current 2 km measurement uncertainty for cloud top height consumes the entire error margin available for the Cloud Base Height EDR, which is also 2 km. The cloud base height EDR measurement uncertainty requirement must conform to that used in specifying the requirements for cloud top height. Performance summaries of the Cloud Base Height EDR in fact confirm that retrieved bases are a function of cloud optical thickness, stratified by cloud top phase.

Table 5. Impact of errors in optical depth on retrieved Cloud Base Height for a cirrus (ice) cloud with cloud top height of 10 km, optical thickness 10, and effective particle size of 100 microns, and ice water content of 0.01 g/m³.

Error in τ (%)	Retrieved Cloud Base Height (m)	Error in Base Height (%)	Calculated Cloud Thickness (m)	Error in Cloud Thickness (%)
0	6689.2	0	3310.8	0
10	7084.5	5.6	2915.5	11.9
20	7463.2	11.5	2536.8	23.4
50	8508.9	27.2	1491.1	55

Errors in retrieved cloud effective particle size

A similar analysis of the retrieval of Cloud Base Height was completed using errors in cloud effective particle size in addition to a 10 percent error in cloud optical depth. Results are shown

in Table 6. The same cloud was used in this exercise as described in Table 3. Again, the errors in Cloud Base Height were insignificant because water clouds are relatively thin, compared to the measurement uncertainty threshold requirement, even for optical thickness values of 64. A similar analysis was deemed unnecessary to draw conclusions about the impact of errors in particle size on ice clouds.

Table 6. Impact of errors in effective particle size on retrieved Cloud Base Height. The cloud is identical to that used in Table 3 except that the optical depth of 64 was assumed to have a 10% error.

Error in r_e (%)	Retrieved Cloud Base Height (m)	Error in Base Height (%)	Calculated Cloud Thickness (m)	Error in Cloud Thickness (%)
0	1440	4.5	560	10
10	1496	8.6	504	19
20	1552	12.6	448	28
50	1720	24.8	280	55

Errors in liquid water content models

A potentially more significant error source surrounds the selection of the appropriate cloud droplet or ice particle distributions used in the retrieval of Cloud Base Heights. The key to the VIIRS Cloud Base Height retrieval is the relationship between LWP and liquid water content (LWC) for water clouds and IWP and IWC for ice clouds. LWC and IWC are generated *a priori* from observations of cloud particle size distributions. The use of LWC and IWC cause two concerns: First, these data are not routinely observed on a global basis thus, actual size distributions may vary by location. For example, LWC for stratus was found to vary from 0.24 g/m^3 over oceans to 0.44 g/m^3 over land while stratocumulus has a value of 0.09 g/m^3. There is often little difference in VIIRS-type imagery between stratocumulus and stratus over the ocean; thus, doubt might arise in determining which LWC should be used in the Cloud Base Height retrieval because the LWC values for these cloud types differ by a factor of nearly 3. Secondly, LWC/IWC values have been found to vary considerably between field measurement campaigns. For example, the IWC for cirrus clouds was considered 0.01 g/m^3 during the 1940s, ~ 0.02 g/m^3 during the 1970s, and most recently 0.006 - 0.30 g/m^3. Such variations may produce an order of magnitude difference in the retrieved Cloud Base Height. While a parameter that measures the effective droplet or particle size distribution is essential for the retrieval of Cloud Base Heights, the logic needed to support this selection process remains an open issue.

Sensitivity analyses were conducted using size distributions published in the literature (Liou, 1992). The results, shown in Table 7, reveal the same trend noted in Tables 3 and 6. While errors in the cloud thickness are quite large, the actual error in Cloud Base Height remains small because any water cloud with an optical depth of 64 is relatively thin compared to the measurement uncertainty threshold requirement with stratocumulus being the one exception

since values for this cloud are many times smaller than those of the other cloud models. This may translate to a requirement for automated cloud-type classification after additional studies are completed using the complete set of cloud EDR algorithms. Errors are scaleable to thicker clouds if the value of optical thickness does not exceed the range used in the parameterizations, shown in Equations 2 and 5. The literature does not define the range of optical thickness values that were used to validate this parameterization.

Table 7. The effect of errors in droplet size distribution, i.e., liquid water content, on retrieved Cloud Base Heights. The cloud is the same as the one used in Table 2 with 10 percent errors in optical depth (assumed 64, used 57.6) and r_e (assumed 3.5 used 3.15 microns).

IWC (actual value = 0.24 g/m³)	Retrieved Cloud Base Height (m)	Error in Base Height (%)	Calculated Cloud Thickness (m)	Error in Cloud Thickness (%)
0	1496	8.6	504	19.0
0.44 (st land)	1725	25.2	275	55.8
0.09 (sc)	656	52.4	1344	116.1
0.66 (cu)	1816	31.8	184	70.4

Errors associated with multiple scattering/multi-layered clouds

The most accurate Cloud Base Height retrievals are obtained for scenarios consisting of single-layered cloud systems when multiple scattering is insignificant, e.g., clouds completely fill the VIIRS field-of-view. As a corollary, the retrieved Cloud Base Heights will be degraded when multi-scattering events occur, as may be the case for with sub-pixel cloud cover or and when optically-thin clouds overlie a highly reflective surface, such as another cloud system. Thus, special emphasis must be place upon the retrieval of Cloud Base Heights for multi-layered cloud systems that occur within the horizontal spatial resolution (HSR) of the VIIRS sensor. A complete analysis of retrieval accuracy of all VIIRS cloud EDRs for multi-layered cloud systems is a post-PDR task.

3.5   ALGORITHMS FOR USE WITH MULTI-LAYERED CLOUD SYSTEMS

Ancillary EDR data products from the CMIS sensor provide essential information for the retrieval of Cloud Base Heights in multi-layered cloud systems. In particular, the LWP and CIWP CMIS data products can be used to improve the retrieval of Cloud Base Heights when multiple-layered cloud systems are analyzed within a single VIIRS HSR, especially over ocean surfaces where the risk is low that these CMIS products will fail to meet NPOESS threshold requirements.

3.5.1   Processing Outline for Multiple-Layered Clouds

The Multi-Layered Cloud Base Height Algorithm retrieves a Cloud Base Height for either ice or water clouds using both VIIRS and CMIS EDRs ancillary data sets. The algorithm retrieves information on at most two cloud layers under the following constraints.

If the phase of the highest cloud in the VIIRS HSR is water, the cloud base height of the highest layer is retrieved using the VIIRS cloud top height, optical thickness, and effective particle size EDRs. The lowest-level water cloud base is determined using either the CMIS cloud liquid water (CLW) EDR or the CMIS cloud base height EDR (Wilheit and Hutchison, 1998; 2000).

If the phase of the highest cloud in the VIIRS HSR is ice, the ice Cloud Base Height is retrieved using the VIIRS cloud top height, optical thickness, and effective particle size EDRs. Again, the lowest-level water cloud base is determined from either the CMIS cloud base height EDR or using the CMIS cloud liquid water (CLW) EDR. In reality, the optimum Cloud Base Height retrieval algorithm for use when multiple cloud layers occur within a single VIIRS HSR must utilize both VIIRS and CMIS data as shown in Figure 6.

Limitations on the information content of the VIIRS Cloud Base Height EDR occur in multi-layered cloud systems since VIIRS data are typically restricted to the highest cloud in the system. For example, if both ice and water clouds are present, the cloud top heights of the ice cloud may be retrieved but might also be degraded by as much as 100 mb (Menzel and Strabala, 1997). The accuracy of Cloud Base Heights retrieved in these weather systems may not meet threshold requirements. Additional research is needed to determine if it is possible to retrieve any useful information on a cloud top height of a lower level water cloud, which is below the ice cloud, and improve the possibility that meaningful Cloud Base Heights can be retrieved in the complex cloud systems.
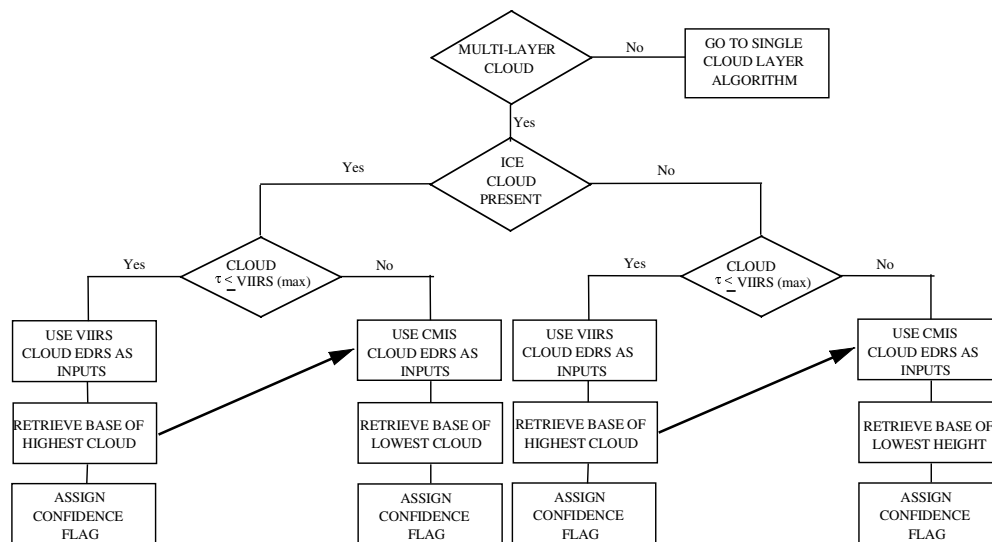
Figure 6. Processing sequence for the retrieval of a multiple-layered cloud system.

In the case where multiple layers of water clouds are present in the VIIRS HSR, the cloud top height and Cloud Base Height of the highest cloud may be retrieved solely from the VIIRS data and Cloud Base Height of the lowest water cloud may be obtained either directly from the CMIS

sensor or with the aid of CLW from the CMIS sensor. However, the retrieved base of the lower cloud might be too high, since the CMIS CLW product represents the entire atmospheric column and cannot provide insight into the number of cloud layers or the distance between any multiple cloud layers. Therefore, the accuracy of Cloud Base Heights retrieved in common wintertime weather systems, i.e., mid-latitude, baroclinic weather systems in which clouds often occur in distinct vertical layers that are separated by cloud-free regions, may not meet threshold requirements. Additional research is needed to determine if the CMIS Cloud Base Height EDR will provide useful information in these cases.

3.5.2   Archived Algorithm Output

There are three outputs from the Multiple-Layered Ice Cloud Base Height Algorithm: (1) a retrieved cloud base height for the highest cloud and (2) cloud base height of the lowest cloud in meters above sea level and (3) a confidence flags for each cloud base height. The confidence flag currently has a value 0-9 which are defined in Section 3.6.4, entitled Quality Assessment and Diagnostics; however, these flags will be updated   to reflect the use of conventional weather observations in the Cloud Base Height Merge Module as a post-PDR task.

3.6   PRACTICAL CONSIDERATIONS

3.6.1   Numerical Computation Considerations

It is assumed that all Cloud Base Height retrievals are made at the HSR of the VIIRS sensor. Results are then summarized to the desired HCS and HRI.

3.6.2   Programming and Procedural Considerations

Cloud Base Height must be retrieved last in the cloud EDR processing sequence.

3.6.3   Configuration of Retrievals

Not available.

3.6.4   Quality Assessment and Diagnostics

A confidence measure or quality flag will be assigned to the retrieved cloud base height using codes defined in Table 8; however, these flags will be updated (TBD) to reflect the use of conventional weather observations in the Cloud Base Height Merge Module. The quality flag is an assessment of the information used to process the cloud EDRs. The quality flag is a function of (1) cloud top phase, e.g., ice versus water cloud top phase of the highest cloud present in the HSR, (2) background characteristics of the scene, i.e., water versus land, (3) whether the cloud optical depth exceeds the VIIRS measurement range threshold requirement, (4) the final retrieval accuracy of CLWP and CIWP EDRs, which are ancillary data provided by the CMIS sensor, and the availability of conventional weather observations, which is still under development and will be discussed in a later version of the ATBD. Retrievals in the presence of multiple cloud layers represent highest risk and results are assigned to lowest confidence level. Conventional data will also be used in assigning confidence flags; however, additional research is needed before a

procedure can be implemented to incorporate conventional data in the quality flag definitions and retrieved Cloud Base Height EDRs.

3.6.5 Exception Handling

Not Available.

Table 8. Current definitions of confidence flags assigned to retrieved cloud base heights.

Code	Definition
9	Single-Layered Water Cloud, Ocean Surface, Optical Thickness $\geq$ VIIRS Measurement Range
8	Single-Layered Ice Cloud, Ocean Surface, Optical Thickness $\geq$VIIRS Measurement Range
7	Single-Layered Water Cloud, Ocean Surface, Optical Thickness $\geq$ VIIRS Measurement Range
6	Single-Layered Ice Cloud, Ocean Surface, Optical Thickness $\geq$ VIIRS Measurement Range
5	Single-Layered Water Cloud, Flat Land Surface, Optical Thickness $\geq$ VIIRS Measurement Range
4	Single-Layered Ice Cloud, Flat Land Surface, Optical Thickness $\geq$ VIIRS Measurement Range
3	Single-Layered Water Cloud, Flat Land Surface, Optical Thickness > VIIRS Measurement Range
2	Single-Layered Ice Cloud, Flat Land Surface, Optical Thickness > VIIRS Measurement Range
1	Single-Layered Water/Ice Cloud, Hilly or Mountainous Land Surfaces
0	Multi-Layered Water/Ice Clouds, Ocean/Land Surfaces, All Optical Thicknesses

3.7 ALGORITHM VALIDATION

There is no heritage algorithm for the retrieval of cloud base heights from passive remotely sensing techniques in the NPOESS or Earth Observing System (EOS) programs. Thus, the feasibility of retrieving cloud base heights must first be evaluated and then the retrieval algorithm must be refined during the post-PDR phase of the VIIRS program.

While the feasibility of retrieving cloud base heights has been demonstrate using simulated DMSP SSM/T-2 microwave moisture sounder data with *a priori* cloud top information from an electro-optical imager as a constraint (Wilheit and Hutchison, 1998; 2000), the VIIRS-only approach and the VIIRS-CMIS approaches outlined in the document represents original research. Thus the algorithm development process follows the conventional approach of proposing the algorithm and using sensitivity studies to perform retrievals with simulated   data. Next, the algorithm must be tested with real sensor data (e.g., MODIS) to ensure that the simulations accurately model real-world phenomenology. The final cloud base height algorithm is then defined and error analyses refined to address accuracy requirements and limitations of the cloud base height retrieval algorithm.

Initial sensitivity studies reported in Section 3 have been completed and some analyses were performed with simulated data as part of the Raytheon Cloud IPT. However, it was quickly realized that limitations inherent to the simulation capability precluded a thorough testing of the Cloud Base Height algorithm. Simulations were performed for a cloud of constant thickness but with variable optical properties, i.e. the cloud was always assumed to be 1 km thick but the optical depth was varied by changing the particle number density. This methodology does not conform to the real word, where clouds of a particular type have characteristic number densities and the optical properties of a cloud varies with its thickness.

3.7.1 Algorithm Testing with MODIS Data from Terra

The task of developing acceptable cases studies to test the accuracy of cloud base height retrievals from MODIS data products is a tedious process. The Terra spacecraft descends over the central US at about 1700 UTC in a sun synchronous orbit and ascends at approximately 0500 UTC. Since solar data are required to retrieve many of the data products needed in the cloud base height retrieval algorithm, e.g. cloud optical depth and cloud effective particle size, only the 1700 UTC data are useful on an annual basis. The test plan begins with simplistic (single-layered) cloud systems and progresses toward more complex scenes.

3.7.1.1 Test Case Preparation

MODIS data and data products derived from the EOS Terra mission are available over the EOSDIS for the initial evaluation of cloud base height algorithms. Since cloud top height is not a MODIS data product, Terra data products must be evaluated along with radiosonde observations to be useful for the retrieval of cloud base heights. Therefore, extensive manual analyses are required to identify suitable test cases and develop ground truth data sets to quantitatively assess the accuracy of retrieved cloud base heights with MODIS data. The process used to evaluate the accuracy of retrieved cloud base heights include the following steps:

3.7.1.1.1 Determination of Cloud Top Height

Eq. (1) and (4) show cloud top height is the key parameter for the retrieval of cloud base height. Unfortunately, the MODIS cloud top parameter products include cloud top phase, cloud top pressure and cloud top temperature but not cloud top height. Converting from cloud top pressure to cloud top height is simple using the Hypsometric Equation if sufficient information is available, i.e. either a priori atmospheric profiles of temperature, pressure and height from a sounder or surface pressure and elevation on the MODIS pixel. Unfortunately, neither product is part of the MOD06_L2 data product list distributed by the EOSDIS. Therefore, it becomes necessary to identify cloud top heights from radiosonde observations. The cloud top height may is near the point where the dew point rapidly dries out in a Skew T Plot as shown in Figure 7. A more precise cloud top height is then analyzed from the significant levels reported in the radiosonde observation, as shown in Table 9. While this is not the ideal method for determining cloud top height, it is acceptable for cases where coincident lidar observations are not available with MODIS data.
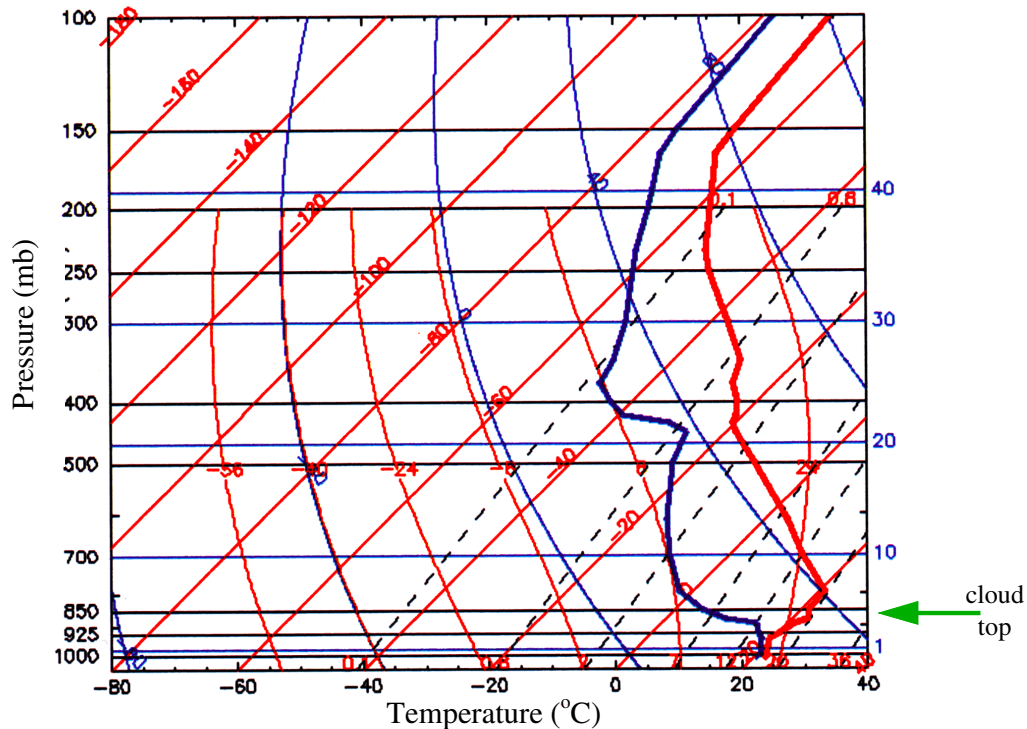
Figure 7. Skew-T plot of Corpus Christi, TX radiosonde at 1200 UTC on April 4, 2001 shows approximate location of cloud top height.

Table 9. Mandatory and significant levels reported in Corpus Christi, TX radiosonde at 1200 UTC on April 4, 2001 accurately reveal location of cloud top height.

Data Type (4 = mandatory 5 = significant)	Pressure (mb)	Height (meters)	Temperature (degree C)	Dew Point (degree C)	Wind Direction (0-360)	Wind Speed (knots)	Remarks
surface	1010	14	21.6	20.4	130	7	
4	1000	102	21.8	20.7	140	10	
5	942	615	19.6	18.3	99999	99999	
4	925	778	20.4	17.1	185	27	
5	894	1071	21.2	15.2	99999	99999	
5	878	1227	22.6	9.6	99999	99999	Cloud Top
4	850	1512	21.4	4.4	200	24	

3.7.1.1.2 Cloud Base Height Ground Truth

As is the case for cloud top heights, ground truth for the cloud base height is best defined using surface base instruments, especially lidar systems. Since these data are not routinely available, the cloud truth cloud base height data is selected from surface observations disseminated by major US airports. Reports from more fully instrumented runways are most useful, especially if both surface and radiosonde observations are available.

3.7.1.1.3 Test Scene Identification

The task of developing acceptable cases studies to test the accuracy of cloud base height retrievals from Terra data is impacted by the system's nodal time, the lack of a MODIS cloud top height data product, and the absence of lidar observations which could serve as cloud top and cloud base height ground truth. Therefore, MODIS data must be compared to a variety of conventional observations to define useful test scenes. Cloud fields are examined in both the visible and infrared GOES imagery at 1200 and 2400 UTC to identify areas that contain potentially useful cloud fields, especially during initial testing which is restricted to cases of single layered, water cloud systems to avoid difficulties of defining bases and tops of ice clouds from radiosonde observations. Such a system is shown in Figure 8 where a single layer of stratus exists across much of Eastern Texas, as confirmed in the radiosonde observations shown in Figure 7 and Table 9. Where cloud fields meet test case requirements, radiosonde and surface observations are collected from NOAA and plots of these data on Skew-T log P diagrams reveal valuable information on cloud top height. Cloud bases are taken from runway surface observations and gross errors checks are made against the radiosonde reports. Surface observations of candidate regions and GOES data are monitored hourly from 1200 UTC until MODIS overflight of the region. If the characteristics of the cloud system do not change during this period, the MOD06_L2 data product is ordered from the EOSDIS. Unfortunately, there is a 60 day processing time to get the MODIS level 2 cloud data products from the EOSDIS that are needed to analyze cloud base heights. For the April 4, 2001 test scene shown in Figures 7 and 8, MOD06_L2 data products will become available in early June 2001. Therefore, the evaluation of the cloud base heights EDR with MODIS data is a lengthy process that includes considerable manual analysis of larger volumes of data to identify useful test cases and patience while waiting for the MOD06_L2 products to become available over the EOSDIS. Testing is now proceeding and verification results are expected to be published in Version 5 of this ATBD.

No cirrus present above
stratus cloud
around
Corpus Christi
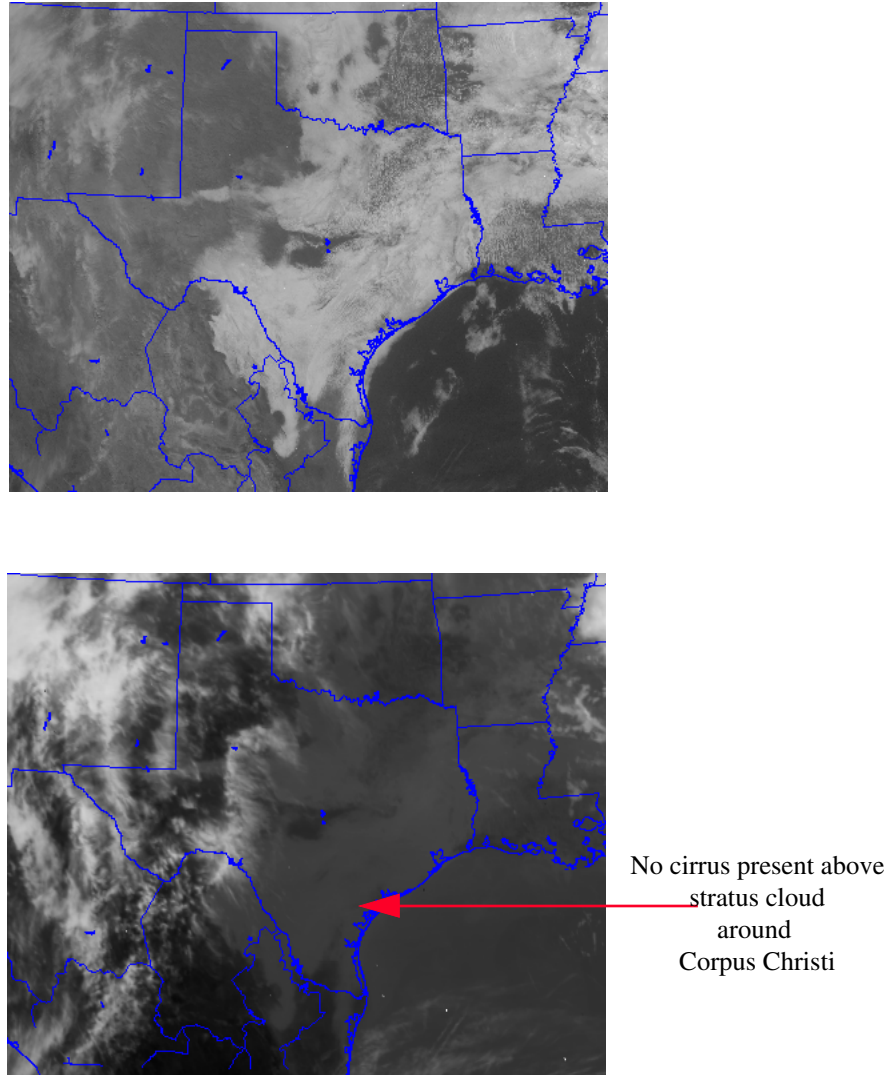
Figure 8. GOES Satellite Imagery of April 4, 2001 Cloud Base Test Case

3.7.2 Algorithm Testing with MODIS Data from Aqua

In the future, we plan to validate the Cloud Base Height EDRs, from both MODIS and the microwave data with the launch of EOS Aqua mission (Hutchison and Wilheit, 2000). The Aqua mission is the first mission which will provide all the data needed to thoroughly test the concepts put forth in this ATBD. We plan to (1) more fully validate the concepts in the VIIRS Cloud Base Height ATBD, (2) test the retrieval of cloud base heights for the microwave algorithm (Wilheit and Hutchison, 1998; 2000), and (3) integrate conventional and in-situ observations into the retrieval of the Cloud Base Height EDR, and finally (4) develop, test, and validate the merger of cloud bases from all these components. However, these activities can only proceed after data

become available with the launch of the EOS Aqua mission. After initial algorithm testing is complete, we will assess performance in accordance with the following stratification plan:

1.   Evaluate results for two surfaces conditions: one with a relatively small albedo in (TBD) VIIRS bands and another surface with a relatively large albedo to evaluate the impact of multiple reflections as a function of cloud optical thickness. The latter is most important to the case where a single layer of optically thin cirrus clouds is present over some reflecting surface.

2.   Evaluate retrieve Cloud Base Height EDRs for two different atmospheric conditions, i.e. with very different attenuation characteristics, especially in the layer defined by the altostratus cloud base and the surface. Thus, the sensitivity studies will consider two atmosphere types (1) a moist profile, e.g., mid-latitude summer and (2) a relatively dry profile, e.g., mid-latitude winter profile.

3.   Evaluations will include sufficient information to describe the dependence of solar illumination and scattering phase angle on the retrieval of cloud base height (Hutchison and Hardy, 1995).

Initially, attention will focus on the analysis of single-layer cloud systems using MODIS imagery. Ground truth measurements will consist of cloud bases obtained from temporally and spatially coincident measurements made by lidar, radar, radiosonde, and surface observations. Finally, the confidence or quality flags, shown in Table 8, will be evaluated and a methodology developed to include conventional data in the quality flag definitions. The quality flag will be extended to include an assessment of any contradictory information processed from either VIIRS cloud EDRs, CMIS EDRs, or ancillary data.

4.0 ASSUMPTIONS AND LIMITATIONS

4.1 ASSUMPTIONS

Assumptions made in the retrieval of Cloud Base Heights are as follows:

Accurate cloud ancillary data will be provided as input fields to the Cloud Base Height algorithms. Most critical are cloud top height, cloud effective particle size, and cloud optical depth. Cloud top phase is also needed to select the water or ice algorithm. An assessment of single versus multiple-layered clouds in the VIIRS HSR is essential.

Sufficient research observations have been made to characterize cloud optical properties, e.g., LWC and IWC, and these values are relatively constant over global conditions.

CMIS threshold requirements will be satisfied over land for the cloud ice water path (CIWP) and CLW EDR products.

Multiple cloud-layers will be differentiated from single cloud-layers in the VIIRS HSR by the Cloud IPT .

4.2 LIMITATIONS

Limitations to the retrieval of Cloud Base Heights are as follows:

The accuracy of the Cloud Base Height is directly proportional to the accuracy of cloud top height. For example, if the cloud top height is in error by 1 km, the retrieved Cloud Base Height will be in error by at least 1 km. The current predicted performance cloud top height is 0.65 for ice clouds and 0.35 km for water clouds.

An effective or mean cloud top height is retrieved for ice clouds while more of a physical cloud top is retrieved for water clouds. Depending upon the complexity of the scene, single versus multiple cloud layers within each HSR, and the optical thickness of the cirrus clouds, the actual error in cloud top heights will vary. Thus, the error in Cloud Base Heights will be worse for ice clouds than for water clouds.

Based upon the predicted performance of the cloud top height EDR, the Cloud Base Height requirement should vary as a function of cloud top phase and optical depth. . However, the SRD does not allocate a larger error for optically thin clouds as compared to optically thick clouds as is done for other cloud EDRs including cloud top temperature, cloud top height, and cloud top pressure.

The accuracy of retrieved Cloud Base Heights will be degraded under the following conditions, which directly affect the retrieval of cloud optical thickness and cloud effective particle size: (a) the presence of multiple-layered cloud systems, (b) the absences of solar illumination, i.e., nighttime conditions, and (c) highly reflective surface, e.g., snow or sparsely vegetated conditions, especially in cirrus cloudy atmospheres.

The retrieval of Cloud Base Heights will suffer in highly variable surfaces, e.g., mountainous terrain, where an average value retrieved for a VIIRS pixel may not be representative of the worst condition.

The accuracy of Cloud Base Heights may be limited by the lack of global *in situ* observations of cloud liquid water content and ice water content. Values from research reported in the literature vary by factors of 2 or 3, and there is no process for taking routine observations from surface meteorological locations, aircraft, or active remote sensing facilities.

5.0   CONCLUSIONS

The results from our investigations persuade us that useful Cloud Base Heights can be retrieved exclusively from remotely-sensed, meteorological satellite data.   This conclusion is based upon the preceding discussions in this ATBD and recently reported information in the refereed literature on the retrieval of cloud base heights from microwave sounder data constrained with cloud top temperature data (Wiheit and Hutchison, 2000). Both the VIIRS and the microwave solutions suggest that Cloud Base Heights with a measurement uncertainty of approximately 1 km are feasible.   However, the demonstration of this capability will require the detailed analysis of key sensor data collected by the EOS Aqua mission, including MODIS, AMSR, and AIRS. In addition, we make the following observations and conclusions about the VIIRS Cloud Base Height retrieval algorithm. Accurate cloud top height is the "driver" for accurate retrieval of Cloud Base Height. As long as cloud top height is known within the predicted performance, it should be possible to meet the threshold values for cloud base heights in single cloud-layered systems for optical depths of 10 or less for ice clouds and 64 or less for water clouds. If cloud top heights are not known to predicted levels, it may not be possible to meet thresholds for the Cloud Base Height EDR.

Cloud top phase is essential for selection size distribution parameters, i.e., LWC versus IWC and effective particle size, r_e versus De. The difference in water concentrations and particle sizes between water clouds and ice clouds is large. Thus, it is critical that information on cloud top phase be provided as a derived EDR. Additionally, by increasing the threshold requirement for cloud optical thicknesses from 10 to 64 for water clouds, it may become necessary to include automated cloud typing as a derived requirement in order to differentiate between stratocumulus, with IWC values of 0.09 g/m^3, and other water clouds with significantly larger values.

The range of optical depths provided by VIIRS has been increased by Raytheon from (0-10) to (0-64); however, this still has limited value for water clouds since $\tau = 64$ corresponds to cloud thicknesses of ~ 500 meters. Thus, the use of VIIRS data for the retrieval of Cloud Base Height must be supplemented by other data sources, such as CMIS data products.

The CMIS may be the most useful source of alternative information on thicker clouds, especially water clouds, through the CLW and CIWP EDRs. However, CLW and CIWP may be considered potentially high risk EDRs, especially over land surfaces because there is no known counterpart to this EDR either in the DMSP SSM/I or EOS AMSR programs.

6.0 REFERENCES

Hutchison, K.D., and K. Hardy (1995). threshold functions for automated cloud analysis of global meteorological satellite imagery. *International Journal of Remote Sensing*, 16, 3665-3680.

Hutchison, K.D., and T. T. Wilheit (2000). An approach for retrieving 3-dimensional cloud fields from data collected by NASA's EOS Aqua mission*, Proceedings of the EUTMETSAT Meteorological Satellite Data User's Conference, Bologna, Italy.*APPENDIX A:

Hutchison, K.D., B.J. Etherton, P.C. Topping, and A.H.L. Huang (1997). Cloud top phase determination from the fusion of signatures in daytime AVHRR imagery and HIRS data. International Journal of Remote Sensing, 18, 3245-3262.

King, M.D., S-C. Tsay, S.E. Platnick, M. Wang, and K.N. Liou (December 1997). Cloud retrieval algorithms for MODIS: Optical thickness, effective particle radius, and thermodynamic phase. MODIS Algorithm Theoretical Basis Document, ATBD-MOD-05.

Liou, K.N. (1980). An introduction to atmospheric radiation. *International Geophysics Series*, 26; New York: Academic Press.

Liou, K.N. (1992). Radiation and cloud processes in the atmosphere. *Oxford Monographs on Geology and Geophysics*, 20; New York, Oxford: Oxford Press.

Menzel, P. and K. Strabala (October 1997). Cloud top properties and cloud phase algorithm theoretical basis document. MODIS Algorithm Theoretical Basis Document, ATBD-MOD-04 (version 5).

Ou, S.C., K.N. Liou, and B.A. Baum (1996). Detection of multilayer cirrus cloud systems using AVHRR data: Verification based on FIRE-III-IFO composite measurements. *Journal of Applied Meteorology*, 35, 178-191.

Ou, S.C., K.N. Liou, W.M. Gooch, and Y. Takano (1993). Remote sensing of cirrus cloud parameters using advanced very-high-resolution radiometer 3.7- and 10.9- mm channels. *Applied Optics*, 32, 2171-2180.

Ou, S.C., K.N. Liou, Y. Takano, N.X. Rao, Q. Fu, A.J. Heymsfield, L.M. Miloshevich, B. Baum, and S.A. Kinne (1995). Remote sounding of cirrus cloud optical depths and ice crystal sizes from AVHRR data: Verification using FIRE-III-IFO measurements. *Journal of Atmospheric Sciences*, 52, 4143-4158.

Rao, N.X., S.C. Ou, and K.N. Liou (1995). Removal of solar component in the AVHRR 3.7 mm radiances for the retrieval of cirrus cloud parameters. Journal of Applied Meteorology, 34, 482-499.

Wilheit, T.T., and K.D. Hutchison (1998). Cloud Base Height Retrieval from DMSP Microwave Data with *a priori* Cloud Temperatures. Proceedings of the 9th AMS Conference on Satellite Meteorology and Oceanography, Paris, France.

Wilheit, T.T., and K.D. Hutchison (2000). Retrieval of cloud base heights from passive microwave and cloud top temperature data. *IEEE Transactions on Geoscience and Remote Sensing*, 18, 1-7.

APPENDIX A   GLOSSARY OF TERMS

Ancillary Data   Any data that is not produced by the NPOESS System, but which NPOESS EDR algorithms require to meet the EDR attributes given in Appendix D (e.g., terrain height data base or conventional surface and upper air observations).

Cloud   An aggregate of minute, nonprecipitating water and/or ice particles in the atmosphere above the Earth's surface. In this TRD, "cloud" is always to be interpreted to mean "detectable cloud" as defined in this glossary.

Cloud Cover   The fraction of a given area that is overlaid in the local normal direction by clouds. It is the fraction of the Earth's horizontal surface that is masked by the vertical projection of clouds.

Cloud Type   The classification of clouds into the 18 types given in Tables 3-19 and 3-20 of the Federal Meteorological Handbook FMH-1B.

Detectable Cloud   An aqueous aerosol having a vertical extinction optical depth exceeding 0.03 (*TBR*) in the visible or a contrast with the background exceeding 0.02 (*TBR*) in the visible. Contrast with the background is defined as the difference between the cloud and adjacent background radiance divided by the sum of these two radiances. In this TRD "cloud" is always to be interpreted to mean "detectable cloud."

Drop Size Distribution   The number of aerosol, cloud, or rain droplets per specified size interval per unit volume over a specified range of sizes.

Environmental Data   Environmental data (also termed "mission data") refers to all data, atmospheric, oceanographic, terrestrial, space environmental, and climatic, being sensed and collected by the satellite or derived, at least in part, from these measurements.

Environmental Data   Data records that contain the environmental parameters or imagery
Records (EDRs)   required to be generated as user products by this TRD as well as any ancillary data required to identify or interpret these parameters or images. EDRs are generally produced by applying an appropriate set of algorithms to Raw Data Records (RDRs).

Horizontal Cell Size	For a parameter that is an estimate of the uniform spatial average of an environmental parameter over a square region of the Earth's surface or within a square layer of the atmosphere, the side length of this square region or layer. (For a parameter that is an estimate of an environmental parameter at a point, the horizontal cell size is defined to be zero.) For a reported parameter not of this type but defined for a square region of the Earth's surface or a square layer of the atmosphere (e.g., cloud cover, ice concentration), the side length of this square region.
Horizontal Reporting Interval	The spacing between nearest neighbor points in the horizontal direction at which an environmental parameter is estimated and reported. For atmospheric profiles the horizontal reporting interval applies to the lowest altitude samples.
Imagery	Two-dimensional array of numbers in digital format that represent the brightness of a small elemental area.
Key Attribute	An EDR attribute that is a key parameter of the system. See Key Parameter.
Key EDR	An EDR that has a key attribute. See Key Attribute.
Key Sensor	A sensor that is required to meet key parameter requirements.
Key Parameter	A parameter so significant that failure to meet the threshold requirement(s) pertaining to its measurement is cause for the System to be reevaluated or the program to be reassessed or terminated. Key parameters include key attributes of key EDRs and the data access requirement. Key parameter requirements are to be included in the Acquisition Program Baseline. (The term "Key Performance Parameter" is used in the IORD.)
Measurement Accuracy	The magnitude of the difference between the mean estimated value of a parameter and its true value (see definition). This estimate may be the result of a direct measurement, an indirect measurement, or an algorithmic derivation. The mean is based on a set of estimates satisfying the following two conditions. The set is large enough so that the sample size error (see definition) in the measurement accuracy is much smaller than the specified measurement accuracy value. The true value of the parameter is the same for all estimates in the set.

Measurement Accuracy (continued)	The second condition is imposed because a measurement accuracy requirement must be met for any true value of the parameter within the measurement range (see definition), not in an average sense over the measurement range. In practice, such as in the analysis of simulation results or measured calibration/validation data, it is understood that measurements will be binned into sets for which the true value of the parameters falls into a narrow range, preferably a range much smaller than the required measurement range.

For an ensemble of N estimates of the parameter x, the measurement accuracy b_N is given by the following formula:

$$b_N = |m_N - x_T|$$

where m_N is the sample mean, x_T is the true value of the parameter, and $|\ldots|$ denotes absolute value. The sample mean m_N is given by the following formula:

$$m_N = (S_{i=1,N}\, x_i)/N$$

where x_i is the value obtained in the i'th estimate of the parameter x and $S_{i=1,N}$ denotes summation from $i = 1$ to $i = N$.

Measurement Error	The difference between the estimated value of a parameter and its true value. This estimate may be the result of a direct measurement, an indirect measurement, or an algorithmic derivation.

The measurement error ε is given by:

$$\varepsilon = x_E - x_T$$

where x_E is the estimate of the parameter x and x_T is its true value (see definition).

Measurement Precision	The standard deviation (one sigma) of an estimated parameter. This estimate may be the result of a direct measurement, an indirect measurement, or an algorithmic derivation. The standard deviation is based on a set of estimates satisfying the following two conditions:

The set is large enough so that the sample size error (see definition) in the measurement precision is much smaller than the specified measurement precision value.

Measurement Precision (continued)	The true value of the parameter is the same for all estimates in the set.
	The second condition is imposed because a measurement precision requirement must be met for any true value of the parameter within the measurement range (see definition), not in an average sense over the measurement range. In practice, such as in the analysis of simulation results or measured calibration/validation data, it is understood that measurements will be binned into sets for which the true value of the parameters falls into a narrow range, preferably a range much smaller than the required measurement range.
	For an ensemble of N estimates of the parameter x, the measurement precision s_N is given by the following formula:
	$$s_N = [\ S_{i=1,N}\ (x_i - m_N)^2/(N - 1)]^{1/2}$$
	where m_N is the sample mean (defined in the definition of measurement accuracy), x_i is the value obtained in the i'th estimate of the parameter x, and $S_{i=1,N}$ denotes summation from i = 1 to i = N.
Measurement Range	Range of values over which a parameter is to be estimated while meeting all other measurement requirements. This estimate may be the result of a direct measurement, an indirect measurement, or an algorithmic derivation.
Measurement Sample Size Error	The standard deviation of the finite sample mean (square root of the variance) over the infinite universal ensemble of possible measurements. The sample size error must be much smaller than the required value of accuracy for any simulation that purports to verify that the accuracy requirement is met.
Measurement Uncertainty	The root mean square (RMS) of the measurement errors (see definition) for an estimated parameter. This estimate may be the result of a direct measurement, an indirect measurement, or an algorithmic derivation. The measurement uncertainty is based on a set of estimates satisfying the following two conditions:
	The set is large enough so that the sample size error (see definition) in the measurement uncertainty is much smaller than the specified measurement uncertainty value.
	The true value of the parameter is the same for all estimates in the set.

Measurement Uncertainty (continued)	The second condition is imposed because a measurement uncertainty requirement must be met for any true value of the parameter within the measurement range (see definition), not in an average sense over the measurement range. In practice, such as in the analysis of simulation results or measured calibration/validation data, it is understood that measurements will be binned into sets for which the true value of the parameters falls into a narrow range, preferably a range much smaller than the required measurement range.
	As defined herein, measurement uncertainty is due to the combined effects of all systematic and random errors. Also, as a consequence of its definition, measurement uncertainty converges to the square root of the sum of the squares (RSS) of the measurement accuracy and precision in the limit of infinitely large sets of measurements.
	For an ensemble of N estimates of a parameter x, the measurement uncertainty ξ_N is given by the following formula:
	$$\xi_N = [\ S_{i=1,N}\ (x_i - x_T)^2/N]^{1/2}$$
	where x_i is the value obtained in the i'th estimate of the parameter, x_T is the true value of the parameter, and $S_{i=1,N}$ denotes summation from i = 1 to i = N.
Objective	A requirement that is significantly more difficult to meet than the threshold requirement but which, if met, would greatly enhance the utility of the data to the users.
Particle Size Parameter	The Angstrom wavelength exponent, alpha, defined as—
	a = -Δln (tau)/ Δln (lambda)
	Where tau is optical thickness and lambda is wavelength, ln denotes natural logarithm, and Δ denotes the difference between optical thickness measurements at two different wavelengths.
Precipitable Water Content	The total amount of water and ice contained in a vertical column of the atmosphere.

Sample Size Error	The standard deviation of a function of a finite set of estimates of a parameter. These estimates may be the result of direct measurement, indirect measurement, or algorithmic derivation. The standard deviation is based on the ensemble of all possible finite sets of estimates. Sample size error is a measure of the width of the probability distribution of a function of a finite set of estimates.

If $\theta_N(x_1, x_2, \ldots, x_N)$ is a parameter depending on N estimates of a parameter x, i.e., $x_1, x_2, \ldots, x_N$, the sample size error is given by the following formula:

$$S_N = \langle\, (\theta_N(x_1, x_2, \ldots, x_N) - \langle\theta_N(x_1, x_2, \ldots, x_N)\rangle\,)^2 \rangle^{1/2}$$

where $\langle\ldots\rangle$ denotes the expectation value over the ensemble of all possible sets of N estimates of x.

The measurement accuracy, precision, uncertainty, and short-term mean (see definition of long term stability) are all examples of functions of a finite set of estimates of a parameter.

Sensor	The mission-peculiar equipment or instrument to be manifested on a given space mission.
Sensor Data Records (SDR)	Full resolution sensor data that are time referenced, Earth-located (or orbit-located for in situ measurements), and calibrated by applying the ancillary information including radiometric and geometric calibration coefficients and georeferencing parameters such as platform ephemeris. These data are processed to sensor units (e.g., radar backscatter cross section, brightness temperature, radiance). Calibration, ephemeris, and any other ancillary data necessary to convert the sensor units back to sensor raw data (counts) are included.
Sensor Suite	One or more sensors needed to satisfy the EDR requirements allocated to a given Sensor Requirements Document (SRD). It does not include sensors from other SRD suites that provide secondary data contributions to those EDRs.
Threshold	The less stringent of the two requirements imposed on each measured or derived parameter. The more stringent requirement is the "objective." (See definition above.) Failure to meet a threshold requirement for a non-key parameter renders the utility of the System questionable, at least to some segment of the user community. Failure to meet a threshold requirement for a key parameter is much more serious and places the entire program at risk. (See definition of "key parameter" above.)

Total Water Content

Total water content has two components:
Total columnar cloud liquid water content (CLWC).
Total columnar integrated water vapor (TIWV).

True Value

True value is defined in terms of *(TBR)* ground truth generally accepted in the user community. When the output of the sensor is folded into atmospheric, radiative transfer and other models to produce EDRs, the measurement uncertainty of the EDR need not be traceable to an absolute reference standard e.g., those maintained by the National Institute of Standards and Technology. The proof of meeting the measurement accuracy, precision, uncertainty, and long-term stability requirements has to be accomplished by analysis, laboratory measurements, simulations, and comparisons to ground-based observations. The proof should include both sensor characteristics and the processing algorithms.

Visible/Infrared

Visible: 0.4 - 0.7 μm
NIR: Near Infrared 0.7 - 1.5 μm
SWIR: Short Wave Infrared 1.5 - 3 μm
MWIR: Medium Wave Infrared 3 - 5 μm
LWIR: Long Wave Infrared 5 - 50 μm